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Research Department Report

BUILDING PENETRATION LOSS MEASUREMENTS FOR DAB SIGNALS AT 211 MHz

J.A. Green, B.A.

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

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Summary

Digital Audio Broadcasting is being considered as a future method of transmitting radio programmes to the public. Some of the advantages of DAB over conventional Frequency Modulation (FM) include its resistance to multipath and its ruggedness in the presence of interference. Because of these qualities it is ideally suited for reception by mobile and portable receivers.

It is proposed that a DAB service will be planned to be effective for use by fixed, portable and mobile receivers. But many problems have to be overcome, to allow accurate planning of suitable transmitter sites and powers, if the desired coverage is to be obtained economically.

This Report gives the results of one aspect of this work, namely the signal level received within a building compared to the level received outside. This is generally termed building penetration loss.

Several different frequency bands are being considered for DAB transmission in the UK. The work reported in this document concentrates on one of the proposed bands: Band III.

The two broad aims of the work were:

1. *By measuring the field strength both inside and outside buildings, determine a Building Penetration Loss figure.*
2. *Using first generation prototype Coded Orthogonal Frequency Division Modulation (COFDM) equipment, find the relationship between field strength and some particular values of Bit Error Ratio (BER).*

A mean building penetration loss of approximately 8 dB has been measured for the whole of the ground floor of brick-built houses.

Using first generation prototype DAB transmitting and receiving equipment, in the absence of interference, a field strength of the order of 39 dB (μV/m) will provide the receiver with an adequate signal.

Further work is essential to quantify the lower limit of field strength in which a final specification receiver will work. There is a potential saving of up to 5 dB on transmitter powers, depending on the particular levels of ambient man-made noise.

Index terms: *DAB; building loss; BER; field strength; mobile measurements*

Issued under the Authority of

Ian Childs

Head of Research Department

Research Department, Engineering Division
BRITISH BROADCASTING CORPORATION

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1. Introduction 1

2. Experimental Arrangement 1

3. Field Strength Analysis 2
   3.1 Field strength on the ground floor 2
   3.2 Field strength on the first floor 3
   3.3 Field strength distributions 3

4. Confidence in the Results 4

5. Bit Error Analysis 4
   5.1 Discussion of BER measurements 5

6. Field Strength and BER 7
   6.1 Ground floor 7
   6.2 First floor 7
   6.3 Incident field strength vs. percentage location coverage on the ground floor 7

7. Basement Measurements 8

8. Discussion, What are the Choices? 8

9. Two Transmitters Radiating Signals into One Building 9

10. Conclusions and Recommendations 9

11. References 10

Appendix 1: First Generation DAB Kit used in 4/2 Mode 11

Appendix 2: Receiver Calibration Figures 12

Appendix 3: Noise Limitations in the Measurement System 13

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BUILDING PENETRATION LOSS MEASUREMENTS FOR DAB SIGNALS AT 211 MHz

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1. INTRODUCTION

Digital Audio Broadcasting (DAB)[1] uses a modulation system which is based on the Coded Orthogonal Frequency Division Modulation (COFDM) technique[2]. The advantages of DAB over conventional Frequency Modulation (FM) include its resistance to multipath and its ruggedness in the presence of interference. Because of these qualities it is ideally suited for reception by mobile and portable receivers.

DAB is being developed as part of a joint European project known as Eureka 147. This is a European collaboration with partners from the broadcasting and consumer electronics industries, research institutes, and from the broadcasters and telecommunications operators.

It is proposed that a DAB service will be planned to be effective for use by fixed, portable and mobile receivers. But many problems have to be overcome, to allow accurate planning of suitable transmitter sites and powers, if the desired coverage is to be obtained economically.

This Report gives the results of one aspect of this work; namely, the level of signal received inside a building compared to the level existing outside. This is generally termed the building penetration loss.

Several different frequency bands are being considered for DAB transmission in the UK. The work reported in this document concentrates on one of the proposed bands: Band III.

The two broad aims of the work were:

1. By measuring the field strength both inside and outside buildings, determine a Building Penetration Loss figure.
2. Using first generation prototype COFDM equipment, find the relationship between field strength and some particular values of Bit Error Ratio (BER).

These two aims were designed to make the link between the field strength outside a building with the percentage of locations inside the building which would receive an adequate signal. In both cases a first generation prototype COFDM receiver was to be used; details of the parameters used in this equipment are given in Appendix 1.

2. EXPERIMENTAL ARRANGEMENT

The BBC installed a six transmitter Single Frequency Network (SFN) in the area south of London. Each of the six transmitters radiated on the Band III frequency of 211 MHz with an effective radiating power (ERP) of 10 watts. The transmissions over one of the audio channels consisted of a pseudo-random bit sequence at 168 kbit/s with rate ½ coding in a bandwidth of 1.75 MHz.

Twenty-six domestic buildings were used in the tests. All of the buildings were at a distance between 300 m and 5 km from the relevant transmitter.

The total received power level was measured on a spectrum analyser and recorded by a portable personal computer. Measurements were triggered by pulses on the blanking output of the analyser. These pulses caused the computer to record a new value each time the analyser updated its display, this was at approximately 0.75 second intervals.

A folded dipole mounted on a 2 m boom was used as the receiving antenna which fed a band-limited amplifier. The total length of feeder between the antenna and the spectrum analyser was approximately 28 m. This length allowed the data-logging equipment to be operated remotely from the antenna, so minimising any risk of computer-generated Radio Frequency Interference (RFI). The long feeder also allowed measurements to be made on different floor levels without the need to carry the equipment up and down stairs.

Bit Error Ratio (BER) data was obtained by counting error events on the output of the DAB receiving equipment. The ratio was generated during 10^5 bits, a new measurement being available every 0.59 seconds.

For each house, each room was measured at two nominal heights: 0.5 m above floor level (a.f.l.) (knee height) and approximately 2 m a.f.l. (shoulder height). The number of measurements which were recorded in each of these sub-sets was largely dependent upon the size of the area and the amount of furniture, etc. situated within it. An area of 25 m^2 typically contains 80 measurements at each height. Field strength values were calculated by adding an equipment calibration figure, K_t, to the power reading of the spectrum analyser. K_t is derived in Appendix 2.

Noise limitations in the measuring system are discussed in Appendix 3.

3. FIELD STRENGTH ANALYSIS

The most useful measurements made outside the building were those in the direction of the transmitter; i.e. between the transmitter and the building. These measurements, at 2 m above ground level (a.g.l.), form the reference field against which all the indoor measurements are compared.

3.1 Field strength on the ground floor

Twenty-three dwellings were measured at 2 m a.g.l. outside and on the ground floor. Three first floor flats were similarly measured. For these dwellings, the outside reference measurements were obtained by leaning out of the first floor windows.

All but one of the buildings were of traditional brick construction. The other building, one of the first floor flats, was built of concrete.

Fig. 1 shows the 50% location attenuation of the field strength on the ground floor of the building compared to the 50% location field measured outside (all field strengths were measured at 2 m a.g.l.). In all buildings, the minimum loss corresponds to the area inside the building which was physically closest to the outside measurement (i.e. signal penetration through one outside wall). The maximum loss corresponds to the area inside the building which was physically furthest away from the outside measurement (signal penetration through the maximum number of walls).

Table 1 shows the mean values and standard deviations for the 50% location penetration losses at 2 m a.g.l.

Table 1
Mean attenuation on the ground floor (at 2 m a.g.l.).

Ground floor measurements	Mean loss dB	Standard deviation
Room with highest field strength	5.0	3.2
Whole ground floor	7.9	3.0
Room with lowest field strength	10.0	3.7

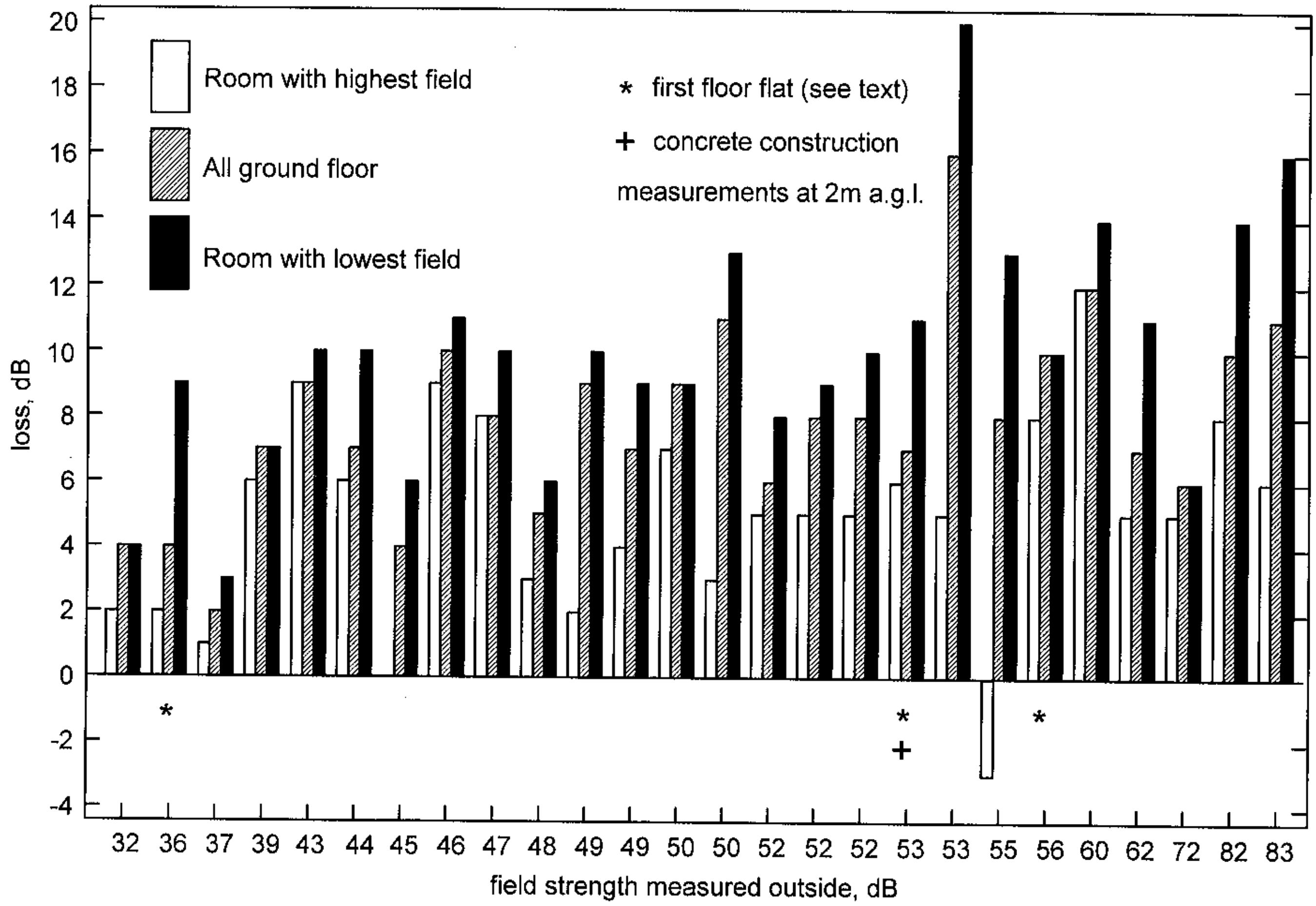

Fig. 1 - DAB signal penetration losses on the ground floor of domestic buildings, 50% location values.

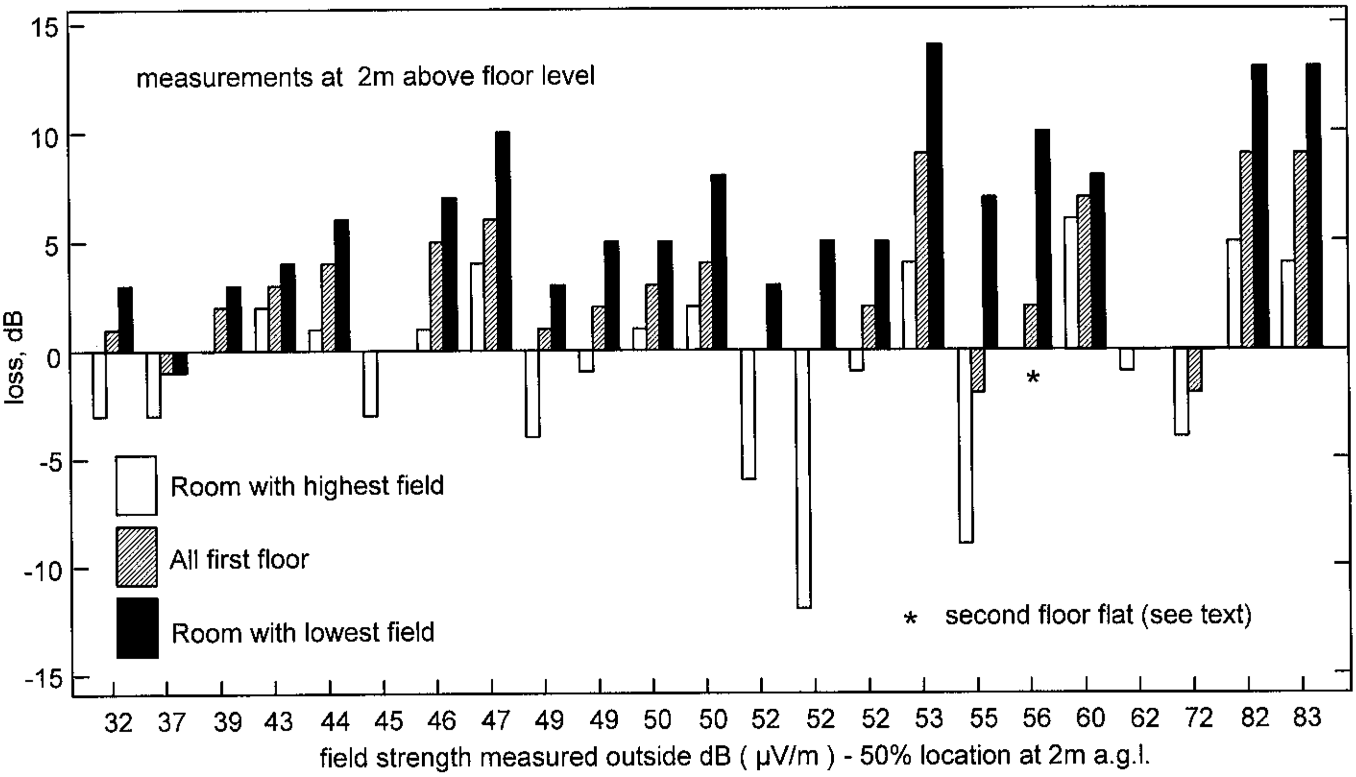

Fig. 2 - Penetration losses of a DAB signal on the first floor of domestic buildings, 50% location values.

3.2 Field strength on the first floor

Twenty-two dwellings were measured at 2 m a.g.l. outside and 2 m a.f.l. on the first floor. One second floor flat is also included, the outside reference measurement was obtained by leaning out of the first floor windows.

Fig. 2 shows the 50% location attenuation of the field strength on the first floor of the building compared to the 50% location field strength measured outside. In all buildings, the minimum loss corresponds to the area inside the building which was physically closest to the outside measurement (i.e. signal penetration through one outside wall). The maximum loss corresponds to the area inside the building which was physically furthest away from the outside measurement (signal penetration through the maximum number of walls).

Table 2 shows the mean values and standard deviations of the 50% location penetration losses at 2.0 m above floor level.

For comparison, the difference between the 50% location field strength values, at 2 m above floor level, measured on the first floor and on the ground floor are shown in Fig. 3 *(overleaf)*. The figure shows the difference between the rooms with the maximum, mean and minimum field strength values.

Table 3 shows the mean values and standard deviations of the difference between the field strength measurements on the first floor and those on the ground floor.

Table 2
Mean attenuation on the first floor (at 2 m a.f.l.).

First floor measurements	Mean loss dB	Standard deviation
Room with highest field strength	−0.7	4.4
Whole of the first floor	2.8	3.4
Room with lowest field strength	5.7	4.3

Table 3
Mean differences between field strength on the first floor and that on the ground floor

First floor - ground floor measurements (at 2 m a.f.l.)	Mean difference dB	Standard deviation
Room with highest field strength	6.0	3.2
Whole of each floor	5.2	2.4
Room with lowest field strength	4.3	2.4

3.3 Field strength distributions

Some 390 areas were measured. For each of these areas the cumulative distribution of field strength

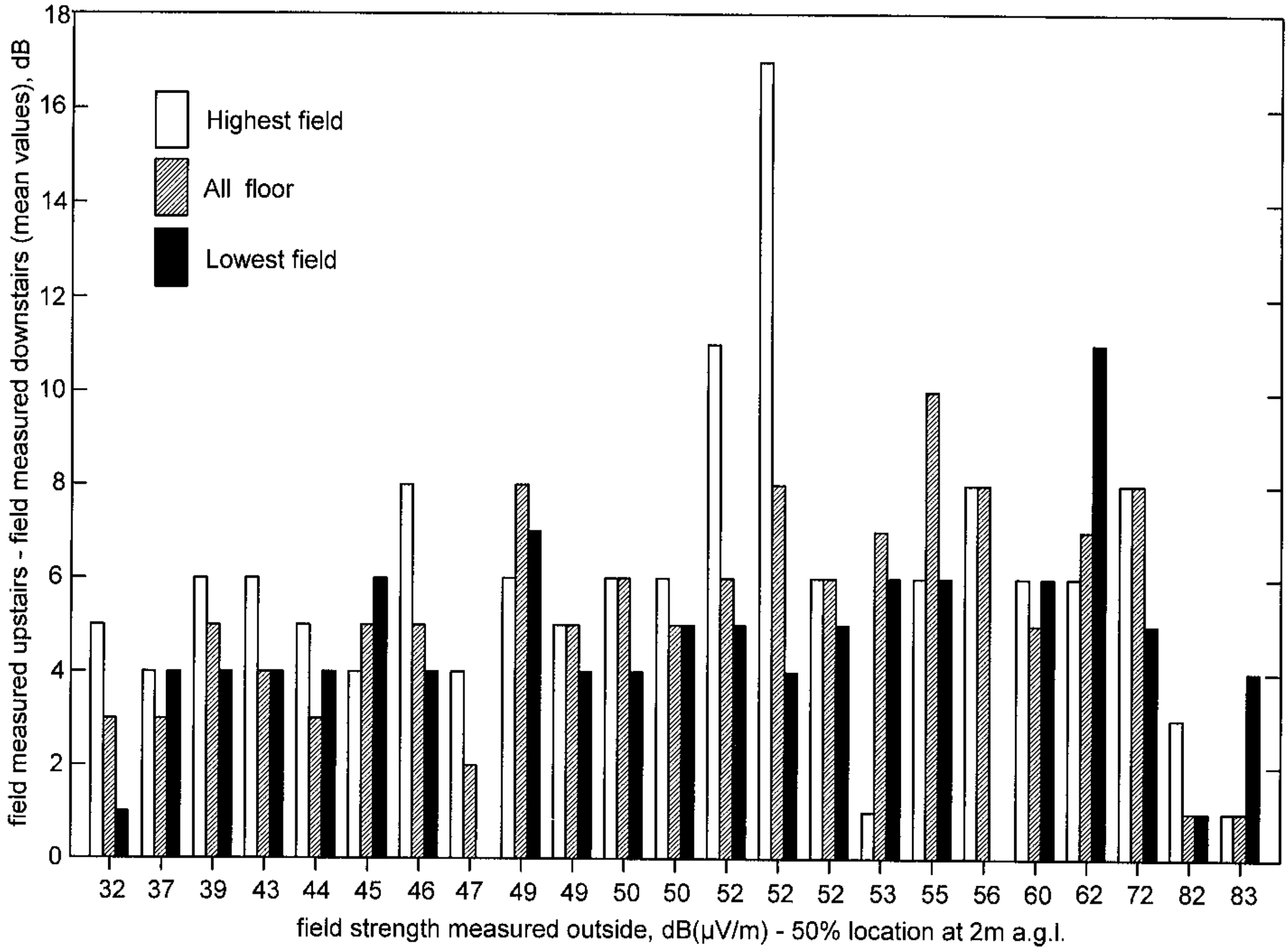

Fig. 3 - Comparison of DAB signals measured upstairs with signals measured downstairs.

tended to log-normal. There was no significant difference in the distributions or the standard deviations of the measurements when comparing areas inside buildings with measurements outside buildings. Nor was there a significant difference in the distributions of field strength measured at 0.5 m a.g.l. and that measured at 2 m a.g.l. The arithmetic mean of the standard deviations for the measurements in all areas was 3.7 dB.

The measurements at 2 m a.g.l. were usually between 3.5 dB and 4.5 dB higher than those at 0.5 m a.g.l.

4. CONFIDENCE IN THE RESULTS

For this sample, taking the worst case (i.e. ground floor) situation:

Mean building attenuation = 7.9 dB

With 95% confidence in the results it can be said that, for Band III, the mean building penetration loss, at 2 m above the ground floor of brick-built houses is:

7.9 dB ± 1.2 dB

It can be shown that if a further 26 buildings were to be measured and give similar results, then the uncertainty in the result would be ±0.8 dB, i.e. a decrease in the uncertainty of 0.4 dB. From this, it is believed that the cost involved in making more penetration loss measurements in brick-built housing cannot be justified.

5. BIT ERROR ANALYSIS

Twelve sets of measurements with bit error information were recorded. Each set comprised measurements of field strength and the bit errors associated with the transmissions of one of the SFN transmitters which were received in and around one building.

To find the practical minimum usable field strength, two thresholds of errors were investigated,

Table 4: Mean of the practical minimum field strengths.

	Mean minimum error free field strengths (dBμV/m)	Standard deviation	Min dB (μV/m)	Max dB (μV/m)
BER >0				
Outside @ 2.0 m	40.0	3.26	36	46
Outside @ 0.5 m	40.4	2.87	35	45
Ground floor @ 2.0 m	39.5	2.23	34	44
Ground floor @ 0.5 m	38.7	2.99	31	44
First floor @ 2.0 m	39.8	3.01	34	47
First floor @ 0.5 m	39.5	2.82	31	45
All measurements	39.6	2.86		
BER $\geq 10^{-3}$				
Outside @ 2.0 m	38.5	2.99	35	46
Outside @ 0.5 m	40.0	2.65	36	45
Ground floor @ 2.0 m	38.2	2.47	32	44
Ground floor @ 0.5 m	37.9	3.32	30	44
First floor @ 2.0 m	38.4	3.19	32	45
First floor @ 0.5 m	38.2	2.81	31	44
All measurements	38.6	2.90		

these were: BER > 0 and BER $\geq 10^{-3}$. For each of the measured areas, the percentage of measurements which had no errors within the thresholds was calculated. The field strength which was exceeded for these percentages of the measurements could then be calculated. Table 4 shows the statistics of these calculations.

Table 4 suggests that, if the received field strength stays above 39 dB(μV/m) then the received BER could be expected to be less than 10^{-3}. If the field strength stays above 40 dB(μV/m) the received BER could be expected to be effectively 0. However, inspection of Table 4 shows a considerable spread of field strength for both stated conditions.

5.1 Discussion of BER measurements

Three points should be noted when using the figures shown in Table 4.

Firstly, because of the implementation of the measuring system, the field strength and BER measurements are not synchronous. While a comparison between the two figures shows a good correlation, they are not exactly matched.

Secondly, synchronisation in the experimental DAB receiver suffers from a hysteresis effect when the BER reaches 0.1. At this BER, the receiver may have lost 'lock' and will then require a relatively high signal level to regain synchronisation. This will tend to make the minimum acceptable field strengths shown above to be pessimistic. However, in noise/interference-free areas, where the minimum receivable field strength is above the values noted above, reception should be acceptable.

Fig. 4 *(overleaf)*, showing field strengths and BERs recorded in one measurement sub-set, shows the effect of the receiver hysteresis.

Thirdly, the noise calculations in Appendix 3 suggest a minimum field strength requirement which varies according to the ambient level of man-made noise. In the absence of man-made noise, the minimum field strength requirement will be 32 dB (μV/m) (18 dB (μV/m) receiver noise 'field strength' + 14 dB c/n). The lowest of the practical minimum field strengths shown in Table 4 is 30 dB μV/m.

Noise measurements during this experimental work inside buildings indicate that a field strength of 37 dB μV/m would be acceptable in 50% of locations. This compares reasonably well with the measured value of 38.6 dB μV/m, shown in Table 4. Other studies out of doors indicates that these figures may be pessimistic.

All subsequent analysis of these building penetration loss measurements will take 39 dB μV/m

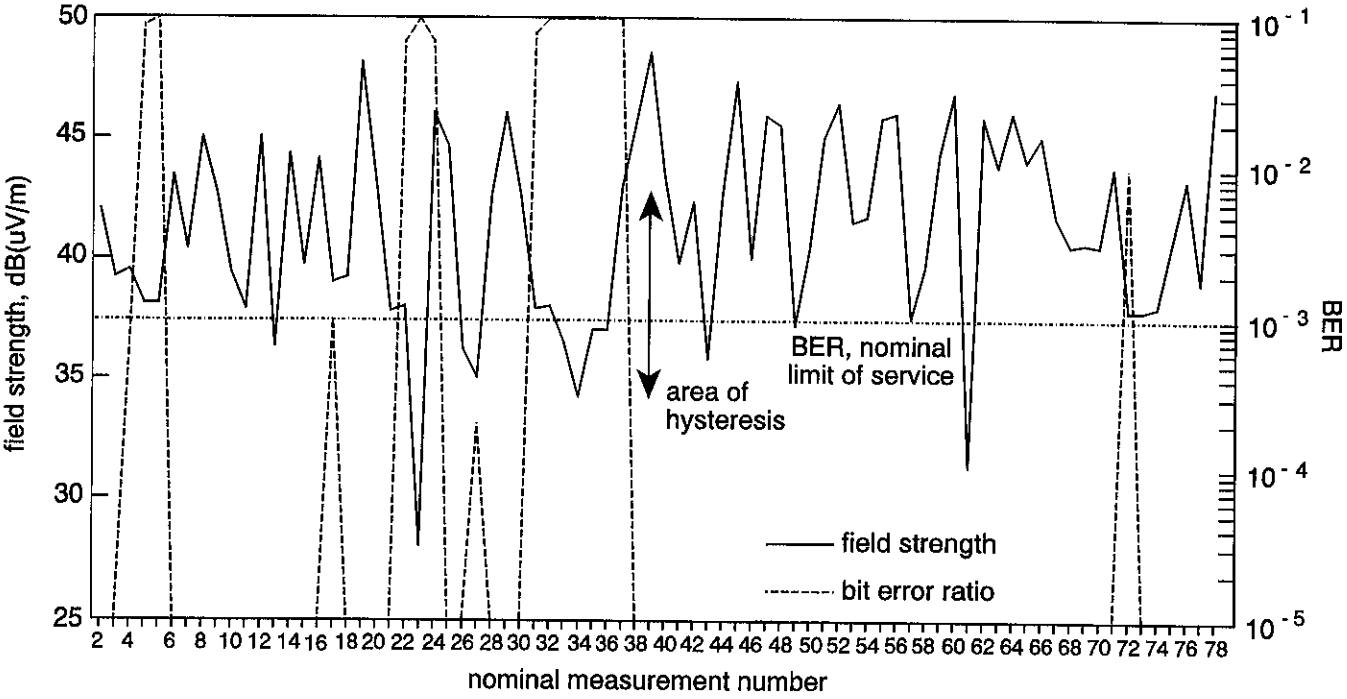

Fig. 4 - Field strength versus bit error ratio.

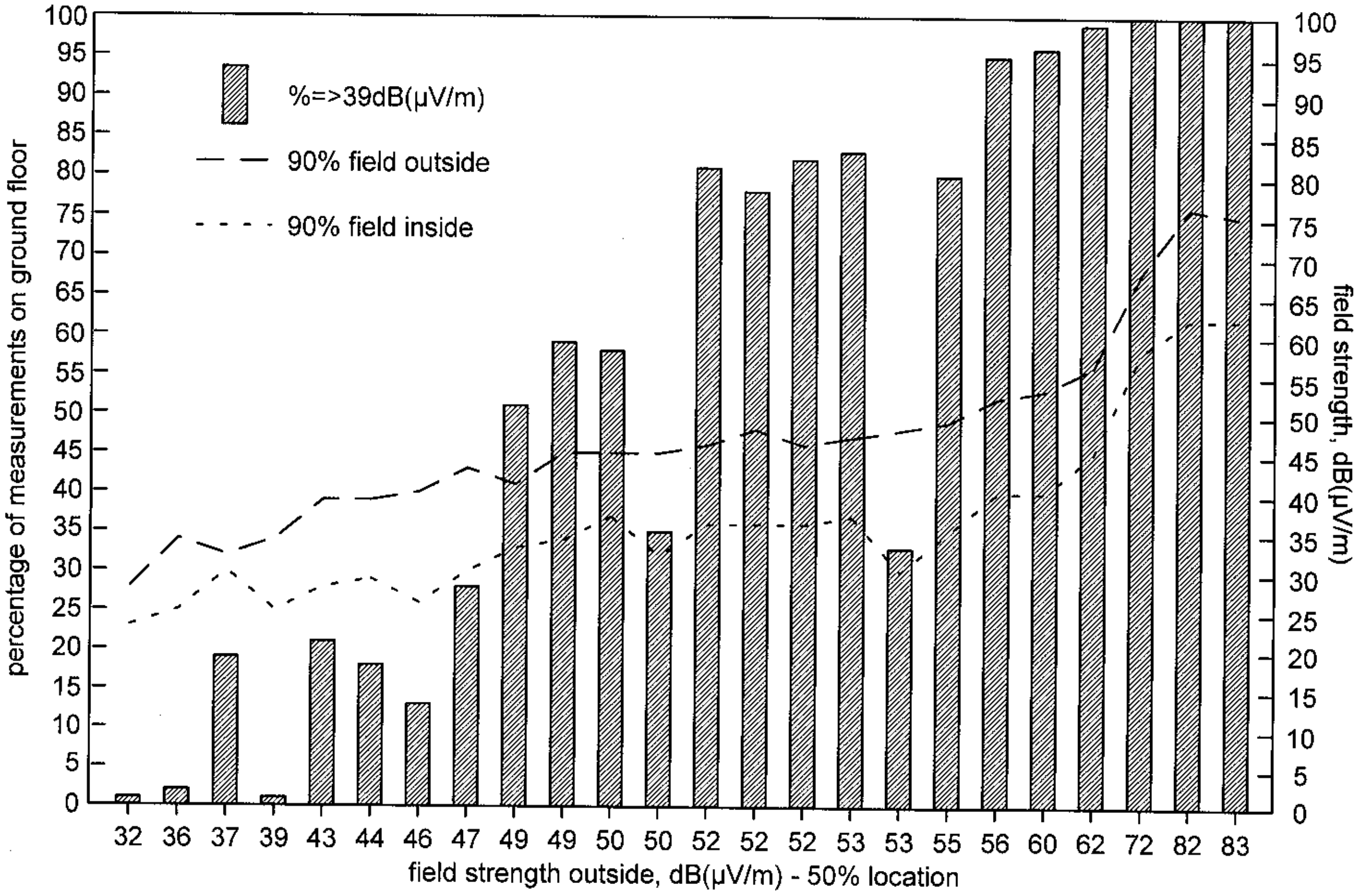

Fig. 5 - Ground floor building penetration measurements.

as the required minimum field strength. The electrical noise produced by the first generation prototype DAB receiver itself (Appendix 3) helps to increase the minimum usable field strength. If future equipment generates less RFI then it may be able to operate satisfactorily in a lower field strength.

Further work is essential to quantify the lower limit of field strength in which a final specification receiver will work. There is a potential saving of up to 5 dB on transmitter powers, depending on the particular levels of ambient man-made noise.

6. FIELD STRENGTH AND BER

6.1 Ground floor

As discussed in Section 5 above, 39 dB (µV/m) is the minimum field strength which will provide a DAB service with a BER of less than 10^{-3}, using existing equipment. Fig. 5 *(opposite)* shows, for each of the measured buildings, the percentage of the ground floor which has a field strength of at least 39 dB (µV/m) — measurements at 0.5 m a.f.l. are also included. As an example, it may be seen from this figure, that, to provide 39 dB (µV/m) to at least 90% of locations on the ground floor of the building, the field strength measured outside, at 2 m a.g.l., must be at least 56 dB (µV/m) for 50% of the locations. This value is liable to change as the COFDM system is further developed.

6.2 First floor

Fig. 6 shows, for each of the measured buildings, the percentage of the first floor which has a field strength of at least 39 dB (µV/m) — measurements at 0.5 m above floor level are also included. As an example, it may be seen from this figure that to provide a 39 dB (µV/m) to at least 90% of the locations on the first floor of the building, the measured field outside, at 2 m a.g.l., must be at least 51 dB (µV/m).

6.3 Incident field strength vs. percentage location coverage on the ground floor

Fig. 7 shows the incident 50% location field strength which will provide a given percentage location of the ground floor with 39 dB (µV/m). The

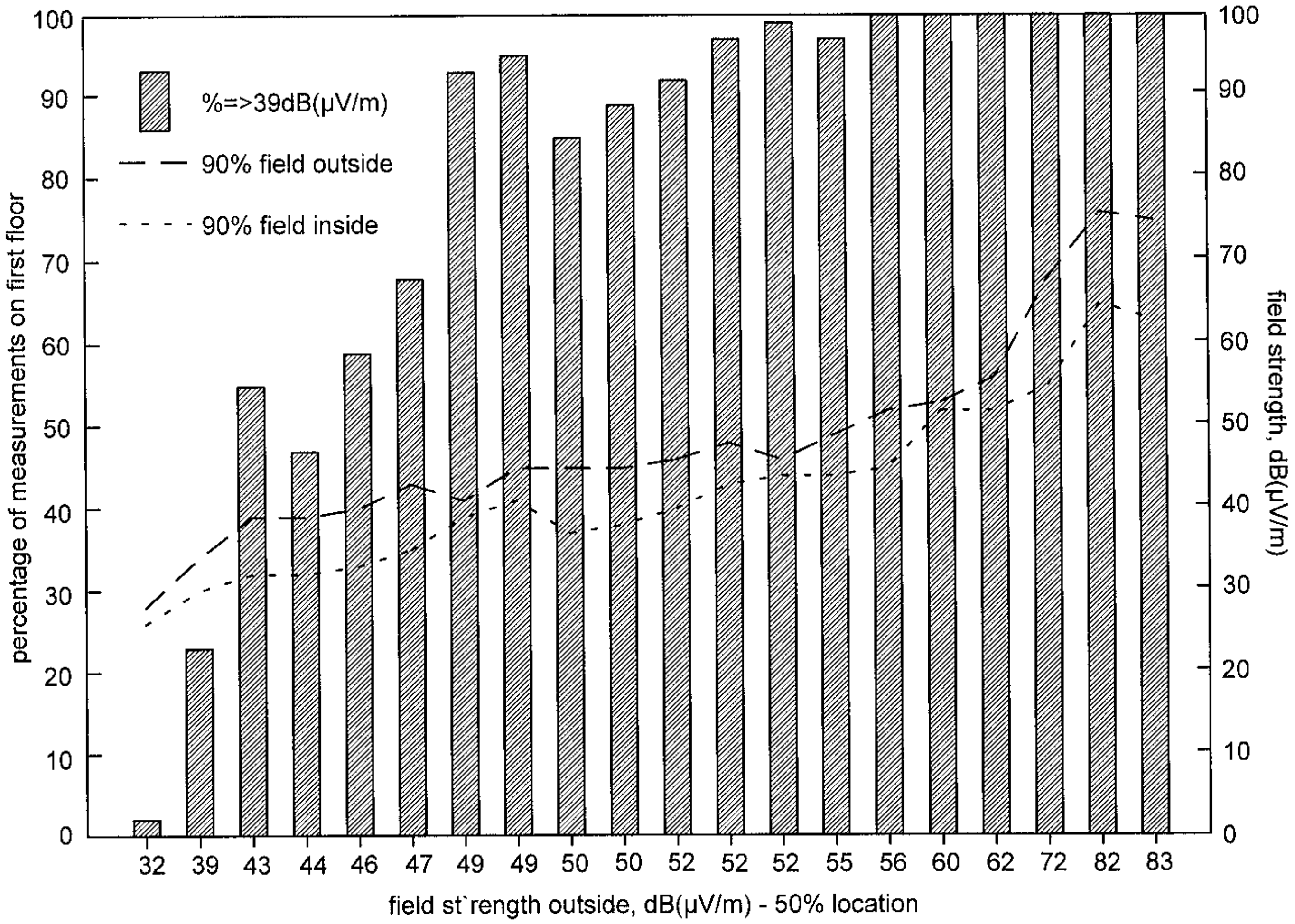

Fig. 6 - First floor building penetration measurements.

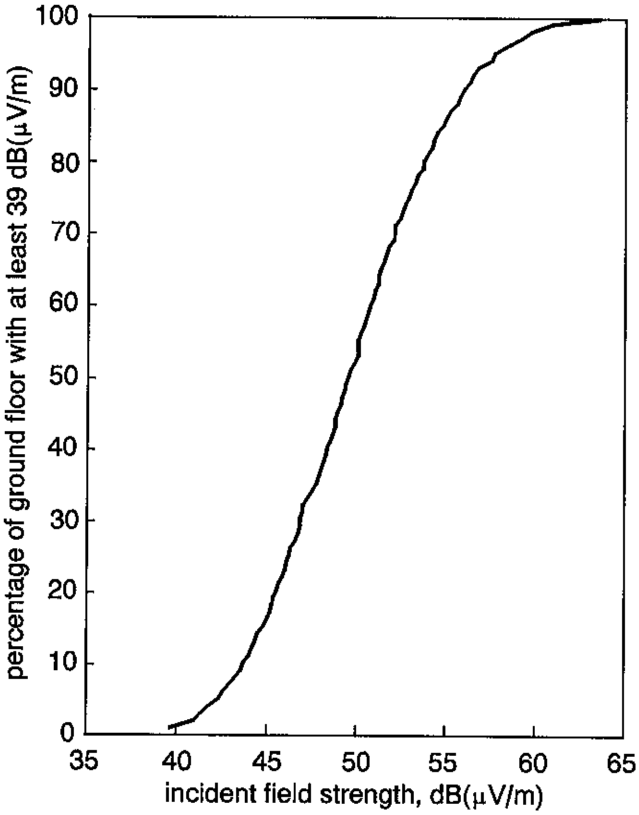

Fig. 7 - Percentage of ground floor coverage as a function of incident field strength.

figure was created using the mean difference between each percentile for the whole of the ground floor (all rooms at both receiving heights) of all buildings. This figure shows a standard deviation of approximately 5 dB compared to a typical figure of 3.7 dB for any room at one height.

As an example of the use of Fig. 7, it may be seen that if 70% of locations were to be the target service area coverage on the ground floor, then the incident 50% location field strength must be at least 52 dB (μV/m).

Note: This is based on a single transmitter; Section 9 below considers two transmitters radiating signals into one building.

7. BASEMENT MEASUREMENTS

Two of the SFN transmitters provided measurable signals into the basement of Kingswood Warren.

At 2 m a.g.l., the attenuation of the field strength from one transmitter into the room above the basement was 7 dB. From the other transmitter, the attenuation was 8 dB. In the basement, the attenuations were 15 dB and 14 dB respectively. This suggests that when transmissions of DAB are required in basement rooms, then a 50% location attenuation of 15 dB should be allowed for. The standard deviations of the measurements in the basement were 3.5 dB and 4.1 dB, this is in keeping with the measurements inside domestic houses.

8. DISCUSSION, WHAT ARE THE CHOICES?

If the aim of a DAB network was to give at least 90% location coverage (BER $<= 10^{-3}$ with first generation equipment) on the ground floor of at least 50% of all brick-built houses, then each dwelling would need a measured 50% location field strength outside, at 2 m a.g.l., of 56 dB (μV/m).

Most people place portable receivers on the tops of tables and work surfaces; these surfaces will usually be about 1 m above floor level, so consideration must be given to such situations. For this purpose an extrapolation can be made, between the measurements at 0.5 m and 2 m above ground level, to obtain a figure for coverage at a 1 m point above ground level.

The average of the standard deviations of each set of ground floor measurements, at 2 m above the ground floor, is 4.3 dB. The height gain between measurements at 2 m and 0.5 m above floor level is, typically, 4 dB. Assuming a linear relationship between height and field strength between these heights, the penetration loss to 1 m above floor level will be 10.5 dB (±1.2 dB). If the aim is to provide coverage for at least 70% of locations on the ground floor at 1 m above floor level, then a 50% location field strength outside (at 2 m above ground level) of:

$$39\,\text{dB}(\mu\text{V/m}) + 10.5\,\text{dB} + 2.2\,\text{dB} = 51.7\,\text{dB}(\mu\text{V/m})$$

is needed;

where:

39 dB (μV/m) is the required field strength

10.5 dB is the penetration loss to 1 m above floor level

2.2 dB ($\sigma/2$) correction for 50% to 70% location

From Section 6.3 above, a field strength outside a building at 2 m a.g.l. of 52 dB (μV/m) would provide 70% location coverage to the whole of the ground floor between the heights of 0.5 m and 2 m a.g.l.

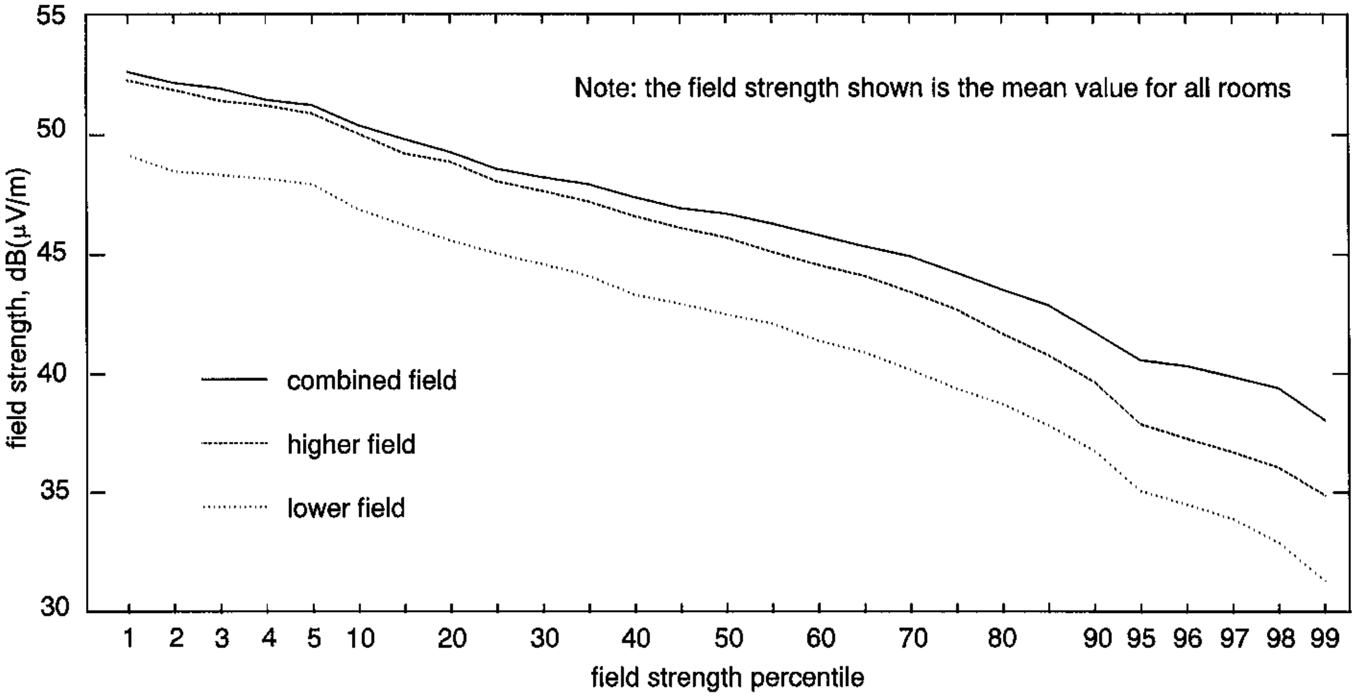

Fig. 8 - Two transmitters radiating signals into one building.

N% coverage on the whole of the ground floor between 0.5 m and 2 m above floor level, is roughly equivalent to N% coverage of the ground floor at 1 m above floor level. However as the 50% location field strength in the room with the most attenuation is, typically, 2 dB below that of the whole floor, 70% coverage on the ground floor is likely to result in 55% coverage in the 'worst' room; while 90% coverage on the ground floor is likely to result in an 80% coverage in the 'worst' room.

9. TWO TRANSMITTERS RADIATING SIGNALS INTO ONE BUILDING

One of the houses received a similar field strength from two transmitters. This building was measured three times, once with each of the two transmitters radiating separately and once with both of the transmitters radiating together. The signal strengths from each transmitter varied from room to room. Because the transmitters were on opposite sides of the building, the signals were stronger in some rooms from one transmitter, while in other rooms the signals were stronger from the second transmitter.

The difference between the field strength from *each* of the two individual transmitters was calculated. The difference between the field strength from the *combination* of both transmitters and the field strength from the *higher* of the two individual contributions was also calculated. These calculations were made for each room and for a number of percentiles of field strength. For each percentile, the mean values for all rooms were calculated and the results are presented in Fig. 8.

These results show that the addition of the second, lower field strength transmission, enhanced the lower field strengths (75% to 99% location values); more than for the higher field strengths (1% to 25% location values). This is achieved because the second transmission helps to fill the field strength minima of the stronger transmission. The average of the standard deviations of the measurements with a single transmitter was 4.0 dB, while that of two transmitters was 3.2 dB.

For each of the percentiles, the contribution of the transmitter with the lower field strength was about 3.3 dB below that of the transmitter with the higher field strength. The mean power gained by the addition of this extra field strength is 1.7 dB, this is also the theoretical figure gained by the addition of a second signal which is 3.3 dB below the first.

10. CONCLUSIONS AND RECOMMENDATIONS

Measurements have been made to assess the loss suffered by a Band III DAB signal as it passes into a domestic building.

A building penetration loss of 8 dB (±1.2 dB with a confidence of 95%) for the whole of the ground floor of brick buildings (2 m a.g.l. outside to 2 m a.g.l. inside) has been derived.

The results of these measurements show that, while using first generation prototype equipment, a received BER $\geq 10^{-3}$ is likely to occur if the received field strength falls below 39 dB (μV/m).

At 211 MHz, a 50% location external field strength of 56 dB (μV/m) at 2 m a.g.l. should provide 39 dB (μV/m) to 90% locations on the ground floor of 50% of all brick-built houses. However, as the 50% location field strength in the room with the most attenuation is typically 2 dB below that of the whole floor, 90% coverage on the ground floor is likely to result in 80% coverage in the 'worst' room.

A graph (Fig. 7) which shows the effect on percentage location coverage by changing the incident field strength is given.

Further work is essential to quantify the lower limit of field strength in which a final specification receiver will work. There is a potential saving of up to 5 dB on transmitter powers, depending on the particular levels of ambient man-made noise.

Two transmitters, with correspondingly lower ERPs will provide better coverage than a single transmitter. This is because a second SFN transmission is likely to fill the field strength minima within the coverage of one transmitter.

A 50% location building penetration loss of 15 dB was measured in one set of basement rooms.

Further work is recommended to determine a building penetration loss figure for other types of buildings, e.g. office blocks, shops and high-rise flats. Figures should also be obtained for other frequencies, e.g. Band I, which may be used to broadcast a DAB service.

The electrical noise which outputs from domestic appliances, such as vacuum cleaners, is a potential interference to a DAB service. Work is required to quantify typical values.

11. REFERENCES

1. EBU, 1992. Proceedings of First International Symposium on Digital Audio Broadcasting. 8th & 9th July 1992.

2. ALARD, M. and LASSALLE, R., 1987. Principles of modulation and channel coding for digital broadcasting for mobile receivers. *EBU Review-Technical*, No. 224, August 1987, pp. 168-190.

APPENDIX 1

First Generation DAB Kit used in 4/2 Mode

Bandwidth = 1.75 MHz

Guard interval = 32 μs

Active symbol period = 128 μs

Total symbol period = 160 μs

Carrier spacing = 7.8125 kHz

Number of active carriers = 224

Convolutional coding/decoding rate = ½

APPENDIX 2

Receiver Calibration Figures

In order to convert the power measurements on the spectrum analyser to field strength, the following calibration (K_t) was added to the readings:

For noise measurements

$$k_n = [Z + S + L_f + P_c] - [G + L_\pi] = 150.5 \text{ dB}$$

where

Z	= Impedance factor	1.6 dB
S	= Receiver termination	6.0 dB
L_f	= Feeder loss	1.0 dB
P_c	= 0 dBW to dBμV (50Ω)	137.0 dB
G	= Antenna gain	2.0 dB
L_π	= Effective length of a half-wave dipole	−6.9 dB

For field strength measurements

$$K_t = [L_b + L_f + L_s + Z + S + P_c] - [G + L_\pi + G_a]$$

where

		Measurements without BER	Measurements with BER
L_b	= Antenna balun loss	0.5 dB	0.5 dB
L_f	= Combined feeder loss	2.7 dB	3.2 dB
L_s	= Splitter	-	6.0 dB
Z	= Impedance factor	1.6 dB	1.6 dB
S	= Receiver termination	6.0 dB	6.0 dB
P_c	= 0 dBW to dBμV (50Ω)	107.0 dB	107.0 dB
G	= Gain of receiving antenna	0 dB	0 dB
L_π	= Effective length of a half-wave dipole	−6.9 dB	−6.9 dB
G_a	= Amplifier + filters	30.5 dB	29.0 dB
		K_t = 94.2 dB	K_t = 102.2 dB

APPENDIX 3

Noise Limitations in the Measurement System

Fig. A3.1 shows a schematic diagram of the front end of the measurement system which was employed during the recording of BERs.

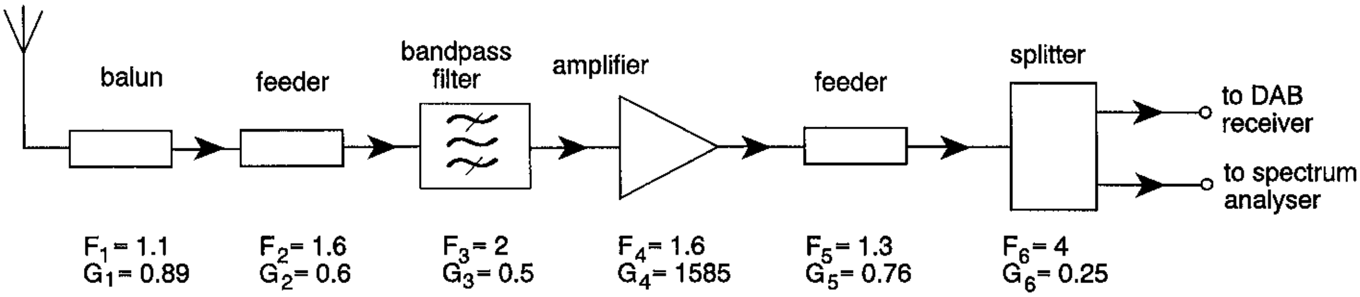

Fig. A3.1 - Schematic diagram of the front end of the measurement system.

The overall noise factor of devices in cascade is given by the formula:

$$F = F_1 + (F_2-1)/G_1 + (F_3-1)/G_1G_2 + \dots.$$

where

F = Noise Factor of item

G = Power Gain of item

From this it can be shown that the effect of the feeder and splitter, which follow the amplifier, are negligible. The overall noise factor of the system is approximately 5.9.

The thermal noise power (P_t) generated in the circuit shown may be calculated as:

$$P_t = kT_aBF \text{ W}$$

where

k = Boltzmann's constant 1.38×10^{-23}

T_a = ambient temperature taken to be 290 °K

B = noise bandwidth of the system = 1.75×10^6 Hz

F = overall noise factor ≈ 5.9

for this system $P_t \approx 4.1 \times 10^{-14}$ W

≈ -104 dBm

The bulk of this noise is generated in the balun, the first feeder, the filter and the amplifier. The gain of the circuit shown is 19.8 dB so the COFDM receiver will 'see' a noise source of −84.6 dBm. Using the system calibration factor, k_t, of 102.2 dB (Appendix 2) this is equivalent to a noise field strength of approximately 18 dB (μV/m).

Current work at BBC Research Department is investigating man-made noise in various environments. A preliminary result of this work for Band III, shows 50% location received noise power levels in Sub-Urban and Urban areas to be of the order −197 dB (W/Hz). The standard deviation of the measurements in any one area was in the range 4 dB to 9 dB. For these outdoor measurements, the receive antenna was a ¼ lambda whip antenna which was centrally mounted on the roof of a saloon car.

Applying a receiver calibration factor, k_n, of 150.5 dB (Appendix 2) and adjusting to a bandwidth of 1.75 MHz, the 50% location man-made noise 'field strength' is $\approx$ 16 dB(μV/m).

By power addition of the thermal and man-made noise sources, we arrive at a 50% location noise field strength of 20 dB (μV/m) in a bandwidth of 1.75 MHz. However, because of the high standard deviation of some of the man-made noise measurement sets, the noise field strength at any location may be considerably higher than 20 dB (μV/m).

A carrier-to-noise ratio of 14 dB is believed to be necessary in order to provide acceptable audio quality in a DAB receiver (work in this area is still in progress). Adding the 14 dB c/n margin to the calculated noise 'field strength' of 20 dB (μV/m), a theoretical minimum acceptable DAB field strength of 34 dB (μV/m) is arrived at.

Some noise measurements were made in houses. Using the same 2 MHz bandwidth as the field strength measurements, 50% location values in the range 17 dB (μV/m) to 27 dB (μV/m) were recorded. Of all the measured areas, half had a 50% location noise field strength of at least 22 dB (μV/m). In this case, power addition of the thermal noise and the measured man-made noise in buildings, gives a 50% location noise field strength of 23 (μV/m). The addition of the 14 dB c/n margin results in a minimum acceptable DAB field strength of 37 dB (μV/m).

Some Radio Frequency Interference (RFI) measurements were recorded near to the DAB receiver. These measurements were made in a bandwidth of 1 MHz centred on 211 MHz. With the receiver switched off the noise floor was 17 dB (μV/m). 10 m away from the working receiver the noise floor was 21 dB (μV/m). 1 m from the receiver the noise floor was found to be 32 dB (μV/m). The measurements indicate that RFI generated by the receiver itself helps to increase the minimum usable field strength of a DAB service. In this experiment, the equipment was outside the premises being measured, and so the penetration loss makes this source of noise negligible.

Electrical noise produced by a selection of vacuum cleaners was measured. These appliances increased the measured noise levels in Band III. The 50% location noise values in rooms with a vacuum cleaner switched on increased to between 31 dB and 38 dB (μV/m). Clearly, the electrical noise generated by some domestic appliances will have a detrimental effect to the minimum usable field strength of a DAB service.